COMPACT SUPERCONDUCTING SYNCHROCYCLOTRONS AT MAGNETIC FIELD LEVEL OF UP TO 10 T FOR PROTON AND CARBON THERAPY

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Abstract

Based on brief analysis of accelerators widely used for proton-ion therapy and patient cure during last 20 years the feasibility and importance of compact superconducting synchrocyclotrons operating at magnetic field level up to 10 T is outlined. The main component of modern commercial facility for proton-ion therapy is an isochronous cyclotron with room temperature or superconducting coils accelerating protons up to 250 MeV as well as synchrotron accelerating carbon ions up to 400 MeV/A. Usually ions are delivered from accelerator into the treatment room by transport lines. Irradiation is done by system of pointed to the patient magnets, collimators, energy degraders which are attached to the rotating Gantry. To greatly reduce price of facility (almost one order of magnitude) and to simplify operational conditions of hospital personal it is proposed to provide iso-centric rotation of compact superconducting synchrocyclotron around the patient. Main physical and technical parameters are described in the paper.

INTRODUCTION

During 60 years proton beams are being used for radiation therapy[1]. Proton resistive tumours are treated by carbon beams [2]. Dedicated commercial facilities for proton/ion therapy are based on 250 MeV synchrotron build by FERMILAB [3] and 400 MeV/A carbon synchrotron HIT [4]. Room temperature cyclotron C235 from Company IBA [5] and superconducting isochronous cyclotron SC250 built by ACCEL [6] are basic accelerator units on the international market. The field level of C235 magnet is 2.17 T and weight is 200 tons while field of SC250 is 3 T and weight is 90 tons. Modern commercial proton therapy complex includes accelerator, beam lines, rotating Gantries and auxiliary equipment. Basic price of Complex is 100-150 M$ and cyclotron cost is only 15% of total price. Special buildings and services are required for such Facility for extra cost.

COMPACTNESS LIMIT FOR 250 MEV ISOCHRONOUS CYCLOTRONS

If one could locate accelerator on rotating carousel platform then ions might be delivered to patient directly – without beam lines and gantry. Compact neutron therapy system with superconducting cyclotron on the rotating platform has been built at NSCL MSU [7,8]. Weght of 50 MeV Deuteron cyclotron is 20 tons. Main condition for rotation of 250 MeV proton machine is the reduction of cyclotron dimensions and weight. Of course one may build rotating platform with 100 tons accelerator on it but there is no commercial interest on such equipment.

Beam energy in cyclotron is $T_k \sim (B_{ext} \cdot R_{ext})^2 Q^2/A$. Magnet weight is $\sim R^2$ (coefficient $\sim R^3$ leads to overstated results). Increasing of field will reduce magnet pole radius and weight. Magnet for 250 MeV cyclic accelerator is weighting 65 tons at field level B=5.5 T and only 20 tons at level B=9 T. Magnet is saturated at high field levels and maximum contribution from iron sectors is ~2 T. Thus flutter is inversely proportional to $F \sim B_{av}^{-2}$ and at the field level of 10 T flutter is only F=0.01.Using of sectors with high spirality $\delta \approx 80°$ ($tg\delta \approx 5$) to improve focusing properties might cause nonlinear instabilities. It is hardly possible to build compact 10 T isochronous cyclotron.

SYNCHROCYCLOTRONS FOR PROTON/ION THERAPY

Main operational principles of synchrocyclotron with weak focusing $0<n<1$ do not impose any limit on the level of magnetic field. In contrast to isochronous cyclotrons there is a possibility to operate synchro-cyclotron with superconducting colis (SC-SC) at high fields. Prof.H.Blosser has proposed to install 5.5T SC-SC on rotating platform [9] and theoretical studies have been performed in NSCL MSU [10,11]. In 2007 Dr. T.Antaya has proposed design of the SC-SC at significantly higher level of magnetic field – up to 10 T (Fig.1) [12]. Private company "Still River" has built "single room" unit for proton therapy "Monarch250" (Fig.2) where compact 9T SC-SC roundabout patient (Fig.3) [13]. The first beam was extracted in May 2010 [14].

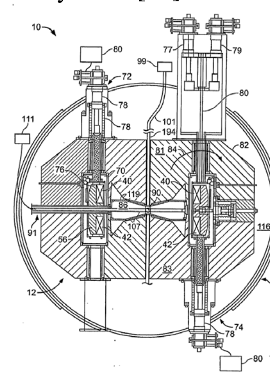

Fig.1. Vertical cross-secion of 9T Synchrocyclotron **[12]**: (81,82,83)–magnet, (40)–Superconducting coils from Nb_3Sn, (70)–cryostat, (119)–Dee, (114)–magnetic shield.

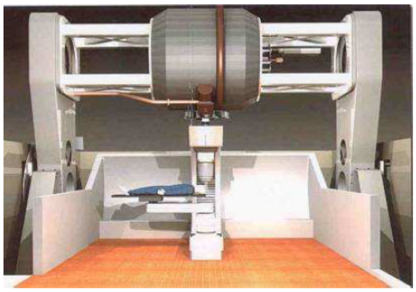

Fig.2. Single room proton therapy unit Monarch250 [13].

Fig.3. Superconducting Synchrocyclotron with 9 T field built by "Still River". Weight is 20 tons. [14].

Another version of compact "single room" proton therapy unit is being built by company ACCEL [15]. Common features of "single room" SC-SC units are:

- High level of magnetic field – 9 T
- Flat poles, azimuthal symmetry
- Weak focusing due to low efficiency of Flatter
- Field slightly drops with radius to ensure axial focusing during acceleration
- RF frequency is reduced to follow relativistics
- Operation by cycles – phase stability
- Low amplitude of Dee voltage
- Moderate beam current but enough for PT

PARAMETERS OF SUPERCONDUCTING SYNCHROCYCLOTRONS

Based on [11,12], we analyse possible parameters of compact superconducting synchrocyclotrons to accelerate protons up to 250 MeV as well as Carbon ions up to 400 MeV/A. In this paper we do not discuss problems related to superconductors at 10T field level. Modern technologies would allow to operate superconductors at 11 T field level and current densities up to 1000A/mm^2 providing A15 Nb_3Sn superconductors of type II cooled down to 4.5° K will be used.

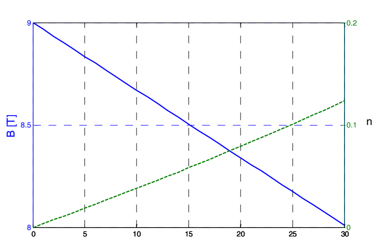

Fig.4. Range of variation of field (1) and field index (2) in the proposed Proton superconducting synchrocyclotron

Table 1. Parameters of synchrocyclotrons for proton/ion therapy

Parameter	Synchro-cyclotron NSCL MSU [4]	Proton Synchro-cyclotron JINR	Carbon Synchro-cyclotron JINR
Ion	protons	protons	C +6
Energy, MeV/A	250	250	400
Beam current, nA	200–400	100–300	100-200
Field, T	5.5-- 4.9	9.1--8	5.8-5
Field index	0.12	0.12	0.12
Radial tune	0.94	≈0.94	≈0.94
Axial tune	0.35	≈0.35	≈0.35
Extr.radius, cm	45	~31	~1.2
Magnet size, cm	264 x 173	185 x 100	420 x 200
Magnet weight, tons	65	25	220
Field azimuthal	symm	4 sectors	4 sectors
Type of Focusing	weak	Weak	Weak
Pole gap-centre, mm	60	25-30	
Pole gap–edge, mm	120	~200	
Flutter	0	0.01	0
Dees	1	2	2
RF harmonic	1	2	4
RF freq.range, MHz	84 / 62	276 /192	178/125
Capture time, μs	~4.5	8	
Repetition rate, kHz	1	1	1
RF voltage, kV	20	20	20
Dee gap, mm	20 / 13	20 / 13	20 / 13
Dee-ground gap,mm	2	2	2
Ion Source	Cold PIG	Cold PIG	ECR
Beam current, mA	1.8	1.8	0.003e

Main parameters of NSCL MSU SC-SC Project as well as our estimations are listed in Table 1. To provide adequat focusing field is reduced from 9 to 8 T and field index is growing to n=0.12 (Fig.4). Axial betatron tune is $\nu_z \approx 0.35$ (fig.5). Extraction radius of 250 MeV protons is 31 cm. Magnet weight is 20 tons. We propose to reduce gap between poles in the center to 25-30 mm with respect to 60 mm in the NSCL MSU design. 180° Dee will not be fitted in such small gap and we consider option to machine azimuthal profile in the magnet pole – 4 straight sectors and 4 valleys. Two 42° Dees will be located in free opposite valleys. 70-100 mm gap in valleys should be enough to allow stable RF operation. In the center field bump is created for axial focusing as well as field profile is shaped to maximize index $\boldsymbol{n}$ in order to improve RF capture efficiency. Regeneratvie type of extraction by exciting of $\nu_r = 2/2$ resonance is used.

Radius of first turn at Dee voltage 20 kV is 2.7 mm. Diameter of ion source Chimney is 3.2 mm and ions of phase band 50° RF will clear central region. Gap between source slit and puller is reduced to 1.5 mm in order to minimize time-of-flight effect. For same reason Dee-Dummy Dee gaps are decreased to 2 mm. Ion source was tested at NSCL MSU and proton beam current is 1.8 mA.

SC-SC will operate at the second harmonic of RF. Span of RF frequency modulation is 84 MHz (fig.6). Repetition rate of cycles is F_{rep}=1000 Hz

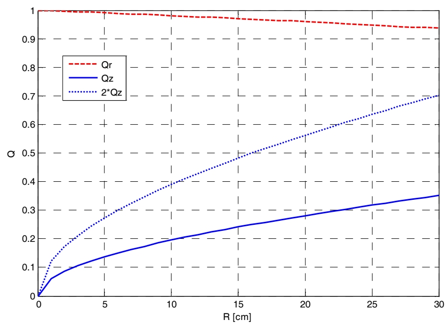

Fig.5. Range of betatron tunes variation: 1–radial tune ν_r, 2 – axial tune ν_z, 3–double axial tune $2\nu_z$. Coupling resonance $\nu_r=2\nu_z$ should not be expected.

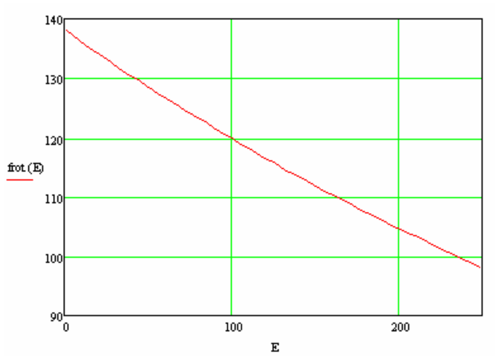

Fig.6. During each operation cycle orbital frequency is reduced from 138 to 96 MHz.

During capture stage the required speed of RF frequency variation is ***df/dt***=70 MHz/ms and maximum slip of RF frequency when ions are still captured into the RF Buckets is 1.9 MHz. Thus capture time of ion bunches into the stable synhrotron oscillations is $\Delta t \approx$5-9 μs. Beam intensity is proportional to capture efficiency in cyclotron $\eta_{cyc} \approx 10\%$ averaged over capture time Δt and repetition rate of RF cycles F_{rep}

$$I_{synchr} = I_{source} \times \eta_{cyc} \times F_{rep} \times \Delta t \times \eta_{extr}$$

Extraction efficiency is $\eta_{extr} \approx$20-40% and average proton beam current from SC-SC should be $I_{synchr} \approx$100–300 nA. During each acceleration cycle speed of RF frequency variation is being optimized. Acceleration might be done in a constant amplitude of RF voltage mode either in a constant energy gain per turn mode i.e. with constant area of separatrix. At fixed amplitude ***V***=20 кВ speed of RF frequency change is adiabatically reduced from 100 to 75 MHz/ms. Acceleration time is ~300μs. In constant energy gain per turn mode ***dE/dN***=10 keV/turn and amplitude of RF voltage is decreased from 20 to 14 kV. Speed of RF frequency modulation is reduced from 100 to 50 MHz/ms. Acceleration time is ~400μs.

SUMMARY

Estimations of possible parameter of Proton and Carbon Synchro-Cyclotrons at 10T field level and comparison with commercial “single room” units being built in USA and Germany allow us come to the conclusion that design of accelerators is feasible and perspective. In case if positive decision will be made to launch projects one has to provide significant amount of simulations and experimental studies. Authors are appreciated to Pr. D.Johnson from “BestCyclotrons” (Canada) for general remarks and Pr. H.Blosser from NSCL MSU (MSU) for kind opportunity to explore results of intensive studies of his students.

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